Tevatron Top Results

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I present the latest results from the CDF and DØ collaborations on top quark production (single top and top quark pair production) at the Tevatron $p\bar{p}$ collider at $\sqrt{s}$=1.96 TeV, measurements of the top quark decay properties such as the branching ratio $\mathcal{B}(t \to Wb)$, the W helicity in $t \to Wb$ decays, and measurements of fundamental parameters such as the top quark charge and mass.

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1. Introduction

The top quark was discovered [1] by the CDF and DØ experiments [2, 3] in $p\bar{p}$ collisions at the Tevatron Run I at $\sqrt{s}$ =1.8 TeV. The Tevatron Run II, which started in 2001, provides now collisions at $\sqrt{s}$ =1.96 TeV with luminosities in the range $0.2-2\cdot10^{32}$cm^{2}s^{-1} and is expected to provide data-sets of several fb^{-1} before the start of the CERN's Large Hadron Collider (LHC). The top quark is of particular interest because it is the heaviest fermion. Its mass is remarkably close to the electroweak scale and it has been speculated that the top quark could be related to the electroweak symmetry breaking mechanism [4]. It is therefore important to measure its properties, not only to characterize it, but also to understand whether it is a mere part of the standard model (SM) or if it is the first sign of new physics beyond it. By virtue of its large mass, the top quark could also decay into exotic particles, e.g. a charged Higgs boson [5]. The top quark has a lifetime of about $0.5 \cdot 10^{-24}$s, much shorter than any other quark. In fact this lifetime is shorter than the QCD hadronization time scale and the top quark decay is about as close as one can get to the decay of a free quark. Understanding the top quark is also important because it will be used as a calibration signal by the LHC experiments and might become the main background to many potential new physics signals, such as supersymmetry. The Run II of the Tevatron with the CDF and DØ experiments are now providing much larger dataset and allow for a series of precision measurements of the properties of the top quark.

2. Top Quark Pair Production

Top quarks can be produced in pairs ($t\bar{t}$) via the strong interaction, mainly via $q\bar{q}$ annihilation at the Tevatron energy. Only pair-produced top quarks have been observed to date, though search for single top

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quark production is intense at CDF and DØ as detailed in next section. The theoretical cross section for $t\bar{t}$ production is $\sigma_{t\bar{t}}$=6.78±1.2 pb [6]. Measuring $\sigma_{t\bar{t}}$ is a test of pQCD at high Q^2. It should be sensitive to exotic top quark decays, since part of the top quark width could "disappear" into exotic channels, for which standard analyzes are not designed. Additional sources of $t\bar{t}$, beyond the SM could also be present, leading to higher values of $\sigma_{t\bar{t}}$. CDF and DØ have measured $\sigma_{t\bar{t}}$ in a range of final states and using various techniques. Figures 1, 2 summarize the measured $\sigma_{t\bar{t}}$ by the CDF and DØ collaborations. The most precise measurements are now limited by systematic uncertainties, from the luminosity measurement and the jet energy scale [7, 8]. The most competitive measurements are carried out in the so-called "lepton-plus-jets" channel, where one of the W boson decay leptonically and one decays hadronically, giving rise to an average of four jets, one isolated high p_T lepton and missing transverse energy ($\not{E}_T$). The value of this channel comes from its relatively high branching fraction ($\sim 30\%$ of $t\bar{t}$ final states), compared to the final state where both W's decay leptonically (so-called "dilepton" channels). It can also be reasonably well separated from the dominant W+jets background, in comparison to the all-hadronic $t\bar{t}$ channel, which has larger branching fraction but contains two hadronically decaying W's and not high p_T lepton. The dilepton final states offer the cleanest signature with two high p_T leptons, but suffer from lower branching ratio ($\sim 5\%$ of the $t\bar{t}$ final states), making measurements in this final state statistically limited. Interesting techniques have been developed to enhance the efficiency for the dilepton channels [9, 10] by identifying one of the leptons purely from its isolated track in the CDF or DØ central tracking system.

3. Single Top Quark Production

The production of a single top quark is possible through weak interaction, mainly via the processes pictured in Fig. 3. The cross section for these processes are σ_t=2.0 pb in the t-channel and σ_s=0.8 pb in the s-channel [11]. The total single top production cross section is not significantly smaller than $t\bar{t}$ pro-
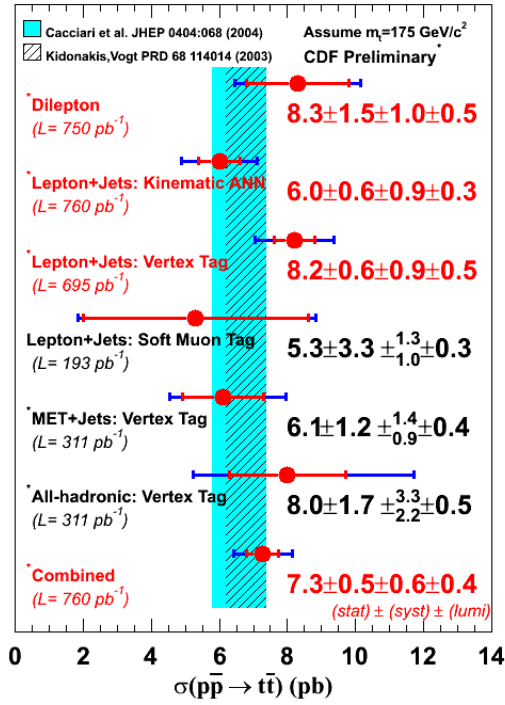
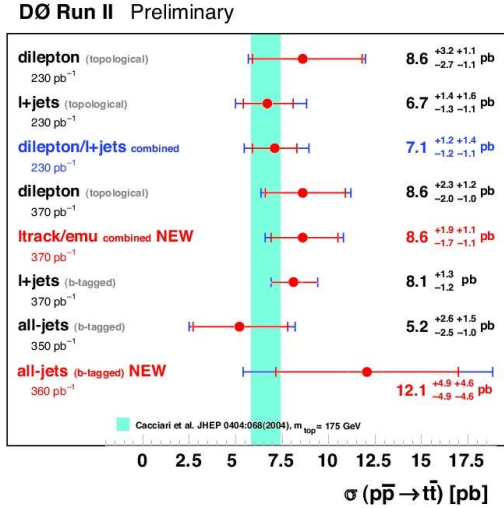Figure 1: Summary of the measured top pair production cross sections measured at CDF.

Figure 2: Summary of the measured top pair production cross sections measured at DØ .

duction cross section, but is significantly more challenging to isolate from backgrounds, due to fewer jets in the final states, and the presence of only one heavy object, instead of two, for $t\bar{t}$.

Single top production is important to search for, as it allows to test that indeed, as predicted by the SM, top quarks can be produced via electroweak interaction. An experimental determination of σ_s and σ_t would provide a direct measurement of the CKM matrix element $|V_{tb}|$, since σ_s and σ_t are proportional to $|V_{tb}|^2$. Single top quark production could also be sensitive to new physics such as extra gauge bosons or additional quarks [12]. Currently, in absence of single top signal, CDF and DØ place upper limits on σ_s and σ_t, which are approaching the region of the cross sections predicted by the SM for the t-channel. The latest measurements are summarized in Table I. The single top signal is searched for in events where the W boson decays leptonically, therefore giving rise to a hight p_T isolated lepton and high $\not{E}_T$. The s-channel has two b-quark jets, whereas the t-channel typically has one b-quark with a light-quark jet. The $\bar{b}$-quark in the t-channel is usually emitted in the forward direction with low p_T and is often undetected. Therefore the two channels have different signatures and the search for the two channels are carried in general separately. The dominant backgrounds are $t\bar{t}$ and $Wb\bar{b}$. The most common analysis method (referred as "2D" in Table I) relies on discriminants, either likelihood-based (LH) or neural network-based (NN). For each channel (s or t) one builds two discriminants D_1 between signal and $t\bar{t}$ and D_2 between signal and $Wb\bar{b}$. Then the expected and observed 2D distributions of D_1 versus D_2 are used to derive the limit on σ_s and σ_t.
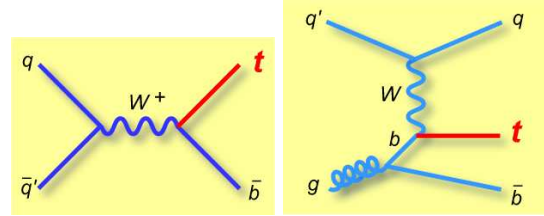

Figure 3: Dominant processes for single top quark production: s-channel (left) and t-channel (right).

Table I Upper limits at 95% C.L. on single top production cross sections obtained by CDF [13] and DØ [14].

	Analysis	Expected	Observed
CDF 695 pb^{-1}	LH: $t+s$	5.9 pb	3.3 pb
	1D NN: $t+s$	5.7 pb	3.4 pb
	2D NN: t	4.2 pb	3.1 pb
	2D NN: s	3.7 pb	3.2 pb
DØ 370 pb^{-1}	2D LH: s	3.5 pb	5.0 pb
	2D LH: t	4.3 pb	4.4 pb
DØ 240 pb^{-1}	2D NN: s	4.5 pb	6.4 pb
	2D NN: t	5.8 pb	5.0 pb

4. Top Quark Branching Fraction to Wb

The top quark decays predominantly via $t \to Wq$, where $q = d, s, b$. Flavor changing neutral current decays of the type $t \to Vq$, where $V = g, Z, \gamma$ and $q = u, c$ are or the order of 10^{-10} or smaller within the SM [15]. Assuming exactly three generations of quarks, the 3×3 quark mixing matrix is unitary, and using the experimentally measured values of V_{ub} and V_{cb} [16], one obtains $0.9990 < V_{tb} < 0.9992$. This also leads to $\mathcal{B}(t \to Wb) \simeq 100\%$. A deviation from the SM prediction could arise in the presence of a 4th quark generation, or contamination of the sample by other processes than $t\bar{t}$. CDF and DØ have both measured $\mathcal{B}(t \to Wb)$ by looking at the fraction of $t\bar{t}$ events with 0, 1 or 2 b-quark jets. Both analyzes assume that $t \to Xq$, where $X \neq W$, is negligible. In events with exactly zero b-quark jets, the S/B is low ($\sim 1/10$), but it is improved with discriminant techniques (artificial neural network for CDF and a likelihood discriminant for DØ) that uses the kinematic properties of the $t\bar{t}$ events. CDF combines both lepton-plus-jets and dilepton final states, DØ uses only lepton-plus-jets final states but fits both the $t\bar{t}$ content and $\mathcal{B}(t \to Wb)$ simultaneously. Both experiments derive lower limits on $|V_{tb}|$ assuming $|V_{tb}| = \sqrt{\mathcal{B}(t \to Wb)}$. The results [17, 18] are summarized in Table II. DØ has also shown that $\sigma_{t\bar{t}}$ and $\mathcal{B}(t \to Wb)$ can be measured simultaneously, which helps to reduce the systematic uncertainties on the top pair production cross section and $\mathcal{B}(t \to Wb)$ [19].

Table II Summary of CDF and DØ measurements of $\mathcal{B}(t \to Wb)$ and 95% C.L. lower limits on $|V_{tb}|$.

	$\mathcal{B}(t \to Wb)$	$|V_{tb}|$ lower limit
CDF 160 pb^{-1}	$1.12^{+0.27}_{-0.23}$	$|V_{tb}| > 0.78$
DØ 240 pb^{-1}	$1.03^{+0.19}_{-0.17}$	$|V_{tb}| > 0.78$

5. W Helicity in Top Decays

In the SM the top quark decays via the V-A electroweak current according to

$$\frac{-ig}{2\sqrt{2}} \bar{b}\gamma^\mu (1 - \gamma^5)|V_{tb}|tW_\mu \qquad (1)$$

where the $\frac{(1-\gamma^5)}{2}$ operator has the effect of reducing the b-quark to its left-handed component. In practice, since the mass of the b-quark is negligible compared to the top quark mass, the top quark decays predominantly to left-handed b-quarks and by angular momentum conservation to left-handed W-bosons. In the SM the fraction of left-handed W's (f^-) is expected to be $\sim 70\%$, and $\sim 30\%$ for f^0, the fraction

of longitudinally polarized Ws. The SM predicts that the fraction f^+ of right-handed W's is $3.6 \cdot 10^{-4}$. A deviation from these predictions could indicate non-SM physics such as large CP-violation in top quark decays [20]. The polarization of the W determines the angular distribution of emission of the lepton in the $W \to \ell\nu$ decay. Therefore one approach to measure $f^\pm$ and f^0 is to measure the distribution of $\cos\theta^*$, where θ^* is defined as the angle of emission of the lepton in the W rest frame, with respect to the top quark line of flight. DØ uses the observed distribution of $\cos\theta^*$ in 370 pb^{-1} of lepton-plus-jets data (Fig. 4) to fit the fraction f^+ [21]. The W polarization affects the p_T of the lepton, since for a left-handed W, $\cos\theta^*$ is closer to minus one, the lepton is emitted in general more anti-parallel to the W boost direction and therefore has a lower average momentum in the lab-frame than for a lepton coming from a right-handed W. The CDF collaboration combines both the observed $\cos\theta^*$ and lepton p_T distributions [22], using lepton-plus-jets and dilepton events to derive the an upper limit on f^+ and a measurement of f^0. Results are summarized in Tab. III.
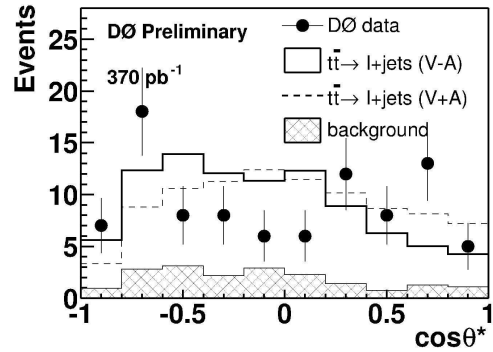

Figure 4: Expected and observed distributions of $\cos\theta^*$ for 370 pb^{-1} of DØ lepton-plus-jets data.

Table III CDF and DØ measurements of W helicity in $t \to Wb$ decays.

	Result
CDF 200 pb^{-1}	$f^+ < 0.27$ at 95% C.L.
	$f^0 = 0.74^{+0.22}_{-0.34}$
DØ 370 pb^{-1}	$f^+ = 0.08 \pm 0.08$ (stat) ± 0.05 (syst)

6. Top Quark Charge

It is widely believed that the heavy particle discovered by the CDF and DØ collaborations is the long-sought top quark. Still, it is possible to interpret the discovered particle as either a charge $2e/3$

or $-4e/3$ quark. In the published top quark analyzes of the CDF and DØ collaborations [23], the correlations of the b-quarks and the W-bosons in the reaction $p\bar{p} \to t\bar{t} \to W^+W^-b\bar{b}$ are not uniquely determined. As a result, there is a twofold ambiguity in the pairing of W bosons and b-quarks, and, consequently, in the electric charge assignment of the "top quark". In addition to the SM assignment, $t \to W^+b$, $''t'' \to W^-b$ is also conceivable, in which case the top quark would actually be an exotic quark with charge $q = -4e/3$. It is possible to make electroweak fits of $Z \to \ell^+\ell^-$ and $Z \to b\bar{b}$ data assuming a top quark of mass $m_t = 270$ GeV and that the right-handed b-quark mixes with the isospin $+1/2$ component of an exotic doublet of charge $-1e/3$ and $-4e/3$ quarks, $(Q1,Q4)_R$ [24]. In this scenario, the $-4e/3$ charge quark is the particle discovered at the Tevatron, and the top quark, with mass of 270 GeV, would have so far escaped detection.

The DØ collaboration has reported [25] the first experimental discrimination between the $2e/4$ and $4e/3$ scenarios. DØ uses 370 pb^{-1} of data, in the lepton-plus-jets channel with b-tagging techniques exploiting the long lifetime of B-hadrons. A very pure $t\bar{t}$ sample is selected by requiring events with at least two b-tagged jets. A kinematic fit is performed on the events in order to fully reconstruct the $t\bar{t}$ event. The b- and $\bar{b}$-jets are separated using a jet charge algorithm that combines the p_T and charge of tracks inside the cone of the b-tagged jet. The expected distribution of jet charge for b- and $\bar{b}$-jets is largely derived from independent collider data-samples. Figure 5 shows that DØ finds the data in good agreement with the SM expectation, and excludes the $4e/3$ scenario at the 94% C.L.
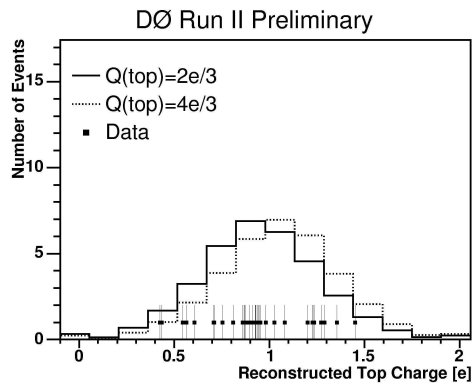

Figure 5: Expected top quark charge distributions in DØ for the SM and exotic scenarios, together with the observed data point.

7. Top Quark Mass

The top quark mass M_{top} is an important parameter of the SM, since it allows to predict the Higgs mass us-

ing precise measurements of the electroweak parameters. At Tevatron, the golden channel to measure M_{top} is the lepton-plus-jets channel thanks to large statistics and significantly better S/B than the all hadronic channel. The CDF and DØ experiments treat separately $t\bar{t}$ candidate events depending on the number of b-tagged jets, to fully exploit specific features of each type of events. For instance double tagged events are fewer, but the S/B is large and the two b-tagged jets allow to significantly decrease the number of possible permutations to reconstruct the $t\bar{t}$ events. On the other hand, events with one or even zero b-tagged jets are less pure, but have larger statistics. It is optimal to exploit the specific features of b-tag multiplicity bin independently and combine them. A relatively recent development in top quark mass measurements is the treatment of the jet energy scale. The uncertainty on M_{top} in the lepton-plus-jets channel is dominated by systematic uncertainties. The dominant source is the jet energy scale. Each lepton-plus-jets event contains one $W \to q\bar{q}'$ decay, giving rise to two hadronic jets whose invariant mass must be consistent with the known W mass. This can be used to simultaneously constrain the jet energy scale as one fits M_{top} to the distribution of observed M_{top}. By carrying out this 2D fit, so called "in situ" jet energy calibration, the systematic error from jet energy scale can be reduced significantly, most of it becoming of statistical nature, and therefore scaling as the square root of the integrated luminosity. A residual jet energy scale systematic uncertainty remains due to *i)* b-jet energy scale, known to be different at a couple of percents level from the light-jet energy scale, and *ii)* the extrapolation of the jet energy scale from the W mass to higher masses.

The currently most performant results from CDF and DØ are summarized in Table IV. The CDF measurement [26] uses the so-called template method [27]. The DØ measurement [28] uses the matrix element method described in Ref. [29]. The top quark mass has also been measured also in dilepton and all hadronic channels [30, 31]. The main measurements are summarized in Figure 6. These results are in good agreement with the electroweak precision measurements from LEP1 and SLD [32] which yields $M_{top} = 172.6^{+13.2}_{-10.2}$ GeV.

Acknowledgments

Table IV Current best Tevatron M_{top} measurements in the lepton-plus-jets channel. For the analyzes using the in-situ jet energy scale calibration, the statistical part of the jet energy scale systematic uncertainty (JES) is grouped with the statistical uncertainty (stat).

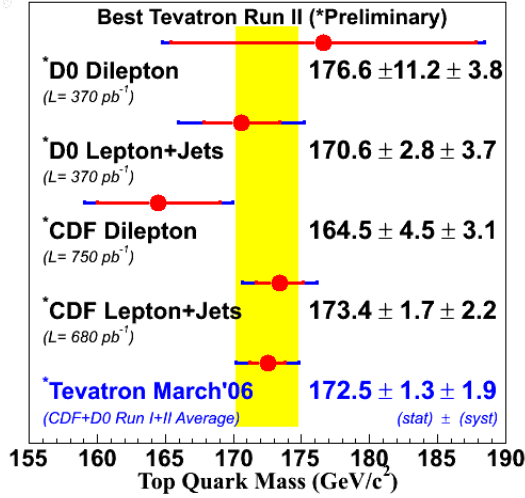|	Measured M_{top} (GeV)
CDF 680 pb^{-1}	173.4 ± 2.5 (stat + JES) ± 1.3 (syst)
DØ 370 pb^{-1}	$170.6^{+4.0}_{-4.7}$ (stat + JES) ± 1.4 (syst)
Combined Run I + II	172.5 ± 1.3 (stat) ± 1.9 (syst)

Figure 6: Summary of measured top quark mass by CDF and DØ .

References

[1] F. Abe *et al.*, The CDF Collaboration, Phys. Rev. Lett. **74**, 2626 (1995); S. Abachi *et al.*, The DØ Collaboration, Phys. Rev. Lett. **74**, 2632 (1995).

[2] See for example J. Cranshaw, The CDF Collaboration, FERMILAB-CONF-00/320-E. Published Proceedings Beauty-2000: 7th International Conference on B-Physics at Hadron Machines, Sea of Galilee, Kibbutz Maagan, Israel, September 13-18, 2000.

[3] DØ Collaboration, V. Abazov *et al.*, "The Upgraded DØ Detector", submitted to Nucl. Instrum. and Methods in Phys. Res. A., physics/0507191.

[4] B. Dobrescu, Phys. Lett. B **461**, 99 (1999); B. Dobrescu, C. T. Hill, Phys. Rev. Lett. **81**, 2634 (1998); C. T. Hill, S. Parke, Phys. Rev. D **49**, 4454 (1994).

[5] J.F. Gunion *et al.*, *The Higgs Hunters Guide* (Addison-Wesley, Redwood City, California, 1990), p. 200.

[6] R. Bonciani *et al.*, Nucl. Phys. **B529**, 424 (1998); N. Kidonakis and R. Vogt, Phys. Rev. D **68**,

114014 (2003); M. Cacciari *et al.*, JHEP **404**, 68 (2004).

[7] The CDF Collaboration, "Determination of the Jet Energy Scale at the Collider Detector at Fermilab", submitted to Nucl. Instrum. and Methods, hep-ex/0510047 (2005).

[8] The DØ Collaboration, Nucl. Instrum. and Methods in Phys. Res. A. **424**, 352 (1999).

[9] The CDF Collaboration, "Measurement of $\sigma(p\bar{p} \to t\bar{t} \to b\bar{b}\ell^+\nu\ell^-\nu)$ at $\sqrt{s} = 1.96$ *TeV*", CDF Conference Note 7942, http://www-cdf.fnal.gov/ (2005).

[10] The DØ Collaboration, "Measurement of the $t\bar{t}$ production cross section at $\sqrt{s} = 1.96$ *TeV* in the combined lepton+track and $e\mu$ channel", DØ Conference Note 5031, http://www-d0.fnal.gov/ (2006).

[11] Q.-H. Cao, R. Schwienhorst, and C.-P. Yuan, Phys. Rev. D **71**, 054023 (2005); Q.-H. Cao *et al.*, Phys. Rev. D **72**, 094027 (2005).

[12] T. M. Tait, C.-P. Yuan, Phys. Rev. D **63**, 014018 (2000).

[13] The CDF Collaboration, CDF Conference Note 7129, "Search for single top quark production with CDF-II", http://www-cdf.fnal.gov/ (2006).

[14] The DØ Collaboration, "Search for single top quark production using likelihood discriminants at DØ in Run II", DØ Conference Note 4871, http://www-d0.fnal.gov/ (2005); Phys. Lett. B **622**, 265 (2005).

[15] G. Eilam, J.L. Hewett, A. Soni, Phys. Rev. D **44**, 1473 (1991).

[16] S. Eidelman et al., Phys. Lett. B **592**, 1 (2004).

[17] The CDF Collaboration, Phys. Rev. Lett. **95**, 102002 (2005).

[18] The DØ Collaboration, submitted to Phys. Lett. B, hep-ex/060302 (2006).

[19] The DØ Collaboration, "Simultaneous measurement of $\mathcal{B}(t \to Wb)/B(t \to Wq)$ and $\sigma(p\bar{p} \to t\bar{t})$", DØ Conference Note 4833, http://www-d0.fnal.gov/ (2005).

[20] H. S. Do *et al.*, Phys. Rev. D **67**, 091501 (2003); J. Cao *et al.*, Phys. Rev. D **68**, 054019 (2003).

[21] The DØ Collaboration, "Measurement of the W boson helicity in top quark decay", DØ Conference Note 5046, http://www-d0.fnal.gov/ (2006).

[22] The CDF Collaboration, submitted to Phys. Rev. Lett., hep-ex/0511023 (2005).

[23] P. C. Bhat, H. Prosper, and S. S. Snyder, Int. J. Mod. Phys. A **13**, 5113 (1998).

[24] D. Chang, W. FG. Chang, and E. Ma, Phys. Rev. D **59**, 091503 (1999); **61**, 037301 (2000); D. Choudhury, T. M. Tait, C. E. Wagner, Phys. Rev. D **65** (2002) 053002.

[25] The DØ Collaboration, "Top charge measurement using jet charge template", DØ Conference Note 4876, http://www-d0.fnal.gov/ (2005).

[26] The CDF Collaboration, "Measurement of the

top quark mass using the template method in the lepton plus jets channel with in situ $W \to jj$ calibration at CDF II", CDF Conference Note 8125, http://www-cdf.fnal.gov/ (2006).

[27] The CDF Collaboration, Phys. Rev. D **73**, 032003 (2006).

[28] The DØ Collaboration, *"Top quark mass measurement with the matrix element method in the lepton+jets final state at DØ Run II"*, DØ Conference Note 5053, http://www-d0.fnal.gov/ (2006).

[29] The DØ Collaboration, Nature 429, **638** (2004).

[30] The CDF Collaboration, *"Measurement of the top quark mass in the dilepton channel using a matrix element method with 750 pb^{-1}"*, CDF Conference Note 8090, http://www-cdf.fnal.gov/ (2006).

[31] The DØ Collaboration, *"Measurement of the top quark mass in the dilepton channel at DØ "*, DØ Conference Note 5032, http://www-d0.fnal.gov/ (2006).

[32] The ALEPH, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavour Groups, *"Precision Electroweak Measurements on the Z Resonance"*, Accepted for publication in Physics Report, hep-ex/0509008 (2006).